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$Z(T_N)$ OBSERVABILITY FOR PARALLEL MULTI-CELL CHOPPER

B. Amghar^(1,2), M. Darcherif^(1,2), J-P. Barbot^(2,3)

1. EPMI, École d'ingénieurs, 13, Bd de l'Hautail - 95092 Cergy-Pontoise, France.

2.ECS-Lab EA 3649, 6 Avenue du Ponceau, 95014 Cergy Pontoise, France.

3. EPI ALIEN-INRIA.

e-mail : b.amghar@epmi.fr, m.darcherif@epmi.fr, barbot@ensea.fr

Abstract - In most industrial processes that use electrical energy as a source of tension or current, requiring a power circuit to control of these physical states. This paper deals with observability problems of the parallel multi-cell chopper. This type of choppers is a new DC/DC static power converter. After modeling of the power converter, its hybrid dynamical behavior and properties are highlighted. The observability properties of the state vector is studied from the new observability concept (The $Z(T_N)$ - observability). Following this observability analysis an adequate sensor placement is proposed after an observability analysis and a super-twisting observer has been proposed, that ensures finite-time convergence and robustness under bounded perturbations. That is why, its estimation by means of an observer becomes an attractive and economical solution. The suitability of the proposed strategy is proved by extensive computer aided simulations employing a comprehensive model of the system considering noisy measurements and load variations.

Keyword - Parallel multi-cell converter, $Z(T_N)$ -observability, Super-twisting observer.

1 INTRODUCTION

The concept of multi-cell converters has been introduced since 1975 [4]. The term multi-cell began with the three-cell converter [5]. Subsequently, several multi-cell converter topologies have been developed [4]. So, the concept of a DC/DC parallel multi-cell converter to achieve higher power is to use a parallel cells each cell constituted of one switch and one inductance with only one voltage dc source. The output current synthesized is equal to n times the input current, where n is the number of cells. Batteries, and renewable energy voltage sources can be used as the dc voltage sources.

The need to regulate the output voltage and current phases requires us to know the dynamics of phase currents and load variations. The use of multiple sensors is the first disadvantage of these kinds of converters. That is why; an observer becomes an attractive and economical solution. In this paper, the concept of observability for switched systems is investigated. The observability of multi-cell converter is analyzed by a new concept called $Z(T_N)$ observability. Following this analysis two observers are proposed. Both are based on the well known super-twisting algorithm coupled with an estimator. So finite time properties and stability of un-

observable parties guaranty the estimation convergence. Moreover, the second integral term of the super twisting algorithm guaranties a good robustness with respect to the noise measurement. Super-twisting observer algorithm is designed for the observation of current phases and voltage output. The observer is set to operate in two cases: the k th switch is closed the observer work, outside the estimator will be operate. The theoretical results are complemented with simulation results verifying performance of the designed observer algorithm. The organization of this paper is as follows. In section 2, the Parallel multi-cell converter modeling is briefly presented. The analysis of the observability of multi-cell converter can be found in Section 3. The observer design is shown in Section 4. While simulation results showing the performance of the observer system are shown in Section 5. Finally, conclusions are presented in Section 6.

2 PARALLEL MULTI-CELL CONVERTER MODELLING

A step-down parallel multi-cell converter is composed by elementary cells of commutation. As it can be seen in Fig.1. In this paper a 5 phase converter and linear load, will be considered a resistive or linear load. The physical switches are considered to be

ideal: in the state on, their voltage is null and in the state off, their current is null.

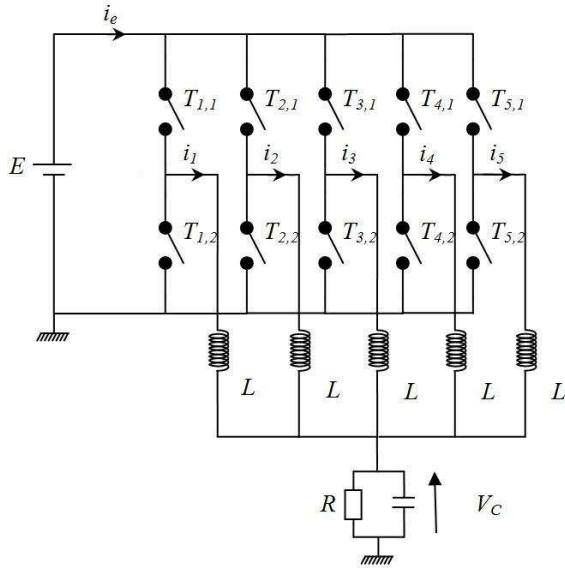


Fig.1. 5-phases parallel multi-cell converter.
Depending on the number of phases and the state of the switch S a multi-cell chopper can be modeled by the following set of differential equations:

$$\begin{cases} L \frac{di_1}{dt} = -R_L i_1 - v_C + s_1 E \\ \vdots \\ L \frac{di_p}{dt} = -R_L i_p - v_C + s_p E \\ C \frac{dv_C}{dt} = i_1 + \dots + i_p - \frac{v_C}{R} \end{cases} \quad (1)$$

where p the number of phases, i_k , $k = 1, \dots, p$ the circulating current through the k phase, v_C the output voltage and s_k the k -phase control input which here value is expressed with the switching function

$$s_k(t) = \begin{cases} 1, & S \text{ closed} \\ 0, & S \text{ open} \end{cases} \quad (2)$$

It is assumed that the inductance value (L) and the resistance value (R_L) are identical for all phases. Considering the case of 5-phases converter and introducing the variables x , y , model (1) can be rewritten in the state form:

$$\begin{aligned} \dot{x} &= f(x, q, t) = A x + B(q) E \\ y &= h(x, q, t) = C(q) x \end{aligned} \quad (3)$$

Where $x = [i_1, i_2, i_3, i_4, i_5, v_C]^T \in \mathbb{R}^6$ is the continuous state, $q = [s_1, s_2, s_3, s_4, s_5]^T$ is the discrete input control. The dynamical matrix A_q and matrix $B(q)$, $C(q)$ defined as:

$$A_q = \begin{bmatrix} \frac{-R_L}{L} & 0 & 0 & 0 & 0 & \frac{-1}{L} \\ 0 & \frac{-R_L}{L} & 0 & 0 & 0 & \frac{-1}{L} \\ 0 & 0 & \frac{-R_L}{L} & 0 & 0 & \frac{-1}{L} \\ 0 & 0 & 0 & \frac{-R_L}{L} & 0 & \frac{-1}{L} \\ 0 & 0 & 0 & 0 & \frac{-R_L}{L} & \frac{-1}{L} \\ \frac{1}{C} & \frac{1}{C} & \frac{1}{C} & \frac{1}{C} & \frac{1}{C} & \frac{1}{RC} \end{bmatrix},$$

$$B(q) = [s_1, s_2, s_3, s_4, s_5]^T$$

$$C(q) = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 & s_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

3 OBSERVABILITY ANALYSIS

Many studies deal with the observability of switched systems using generally either geometric tools or linear time-varying system theory. In these studies, the notion of $Z(T_N)$ -observability are defined to characterize the ability of state reconstruction using the knowledge of the discrete input and the continuous output (see [2] for further details). Hence, it is important to give the following definitions.

Definition 1: A hybrid time trajectory is a finite or infinite sequence of intervals $T_N = \{I_i\}_{i=0}^N$ such that

* $I_i = [t_{i,0}, t_{i,1}]$, for all $0 \leq i \leq N$;

* For all $i \leq N$, $t_{i,1} = t_{i+1,0}$

* $t_{0,0} = t_{ini}$ and $t_{N,1} = t_{end}$

Moreover, $\langle T_N \rangle$ is defined as the ordered list of q associated to T_N (i.e. $\{q_0, \dots, q_N\}$ where q_i is the value of q on the interval I_i).

Definition 2: consider a hybrid dynamical system of parallel multi-cell shopper (3) and a variable $z = Z(t, x)$. The function $z = Z(t, x)$ is said to be $Z(T_N)$ observable with respect to the hybrid time trajectory T_N and $\langle T_N \rangle$ if for any two trajectories, $(t, x^i(t), u^i(t))$, $i = 1, 2$ defined in $[t_{ini}, t_{end}]$ the equality

$$h(x^1(t), u^1(t)) = h(x^2(t), u^2(t)) \text{ Implies}$$

$$Z(x^1(t), u^1(t)) = Z(x^2(t), u^2(t)) \text{ in } [t_0, t_1]$$

Lemma 1: Consider the system (3) and a fixed hybrid trajectory T_N and $\langle T_N \rangle$. Suppose $z = Z(t, x)$ is always continuous under any admissible control input. Suppose there exists a sequence of projection P_i , $i = 0, 1, \dots, N$ such that

(1) given any $0 \leq i \leq N$, $P_i Z(x(t), u(t))$ is $Z(T_N)$ -observable on the subinterval $t \in [t_{i,0}, t_{i,1}]$;

(2) $\text{rank}[P_0^T, \dots, P_N^T] = \dim(Z) = n_z$;

(3) $\frac{dP_i Z(x(t), u(t))}{dt} = 0$ for $t \in [t_{i,0}, t_{i,1}]$,

where $\{\bar{P}_i^T, P_i^T\}$ has a full rank in $\mathbb{R}^{dim(Z)dim(Z)}$. Then, z is $Z(T_N)$ -observable with respect to the hybrid time trajectory T_N and $\langle T_N \rangle$.

Lemma 2: The first condition of Lemma 1 implies that there is at least a time interval in which the variable $P_i Z(x(t), u(t))$ is $Z(T_N)$ -observable; whereas the second one implies that all the components of z are observable in a given time interval T_N of the hybrid time trajectory. The third condition requires that components of z which are not observable in I_i must be a linear dynamic. The application of Lemma 1 to the parallel multicells converter yields the following result: Consider the system (1) and the function $z = x$. Then, z is $Z(T_N)$ -observable with respect to the hybrid time trajectory T_N and $\langle T_N \rangle$ if $rank\{q_i\} = p-1$.

$$\text{where } \{q_i\} = \begin{bmatrix} q_1 & \dots & 0 & 0 \\ 0 & \ddots & \vdots & 0 \\ 0 & \dots & q_{p-1} & 0 \\ 0 & \dots & 0 & q_p \end{bmatrix}$$

Remark 1: this proposition was used in order to studied the serial multi-cell chopper observability with respect to the hybrid time trajectory, moreover a proof of the proposition was given

Now, in order to deal with the case of parallel multi-cell chopper, the class of considered system is the following one:

$$\begin{aligned} \dot{X} &= A_q X + B_q u, \quad q \in Q, \quad X \in \mathbb{R}^n, \quad u \in \mathbb{R}^m \\ y &= C_q X \end{aligned} \quad (4)$$

where, the matrices A_q , B_q and C_q are of appropriate dimensions.

Proposition 2 Consider the system (5) and a fixed hybrid time trajectory T_N and $\langle T_N \rangle$. Let U be an open set in time-state-control space. Suppose $Z(t, X(t), u(t))$ is equal to $X(t)$. Suppose there exists a sequence of projections P_i , $i = 0, 1, \dots, N$ and a positive definite function $V : \mathbb{R}^{n_z} \rightarrow \mathbb{R}^+$, such that

(1) given any $0 \leq i \leq N$, $P_i Z(t, \xi, u)$ is Z -observable in U on the subinterval $t \in [t_{i,0}, t_{i,1}]$;

(2) $Rank[P_0^T \dots P_N^T] = dim(Z) = n_z$;

(3) $V(Z) = V(P_i Z) + V(\bar{P}_i Z)$;

(4) $\dot{V}(\bar{P}_i Z) = \frac{\partial V(\cdot)}{\partial Z} \big|_{\bar{P}_i Z} \bar{P}_i A_i \bar{P}_i Z < 0 \quad \forall \bar{P}_i Z \neq 0$ for $t \in [t_{i,0}, t_{i,1}]$ and $(t, X(t), u(t)) \in U$.

Then, $z = Z(t, X, u)$ is $Z(T_N)$ -observable in U with respect to the hybrid time trajectory T_N and $\langle T_N \rangle$.

Proof From condition (1) using for example a finite time observer based on the super Twisting algorithm [3], there exists $t_{i,c}(t_{i,0} \leq t_{i,c} \leq t_{i,0} + k_i(t_{i,1} - t_{i,0}))$ where $k_i \in [0, 1[$ will be defined later) such that

$$P_i e = e_{p_i} = 0 \quad \forall t \in [t_{i,1}, t_{i,c}]$$

e_{P_i} is the observation error on the observable subspace during the time interval T_i , in the same way $e_{\bar{P}_i}$ denotes the estimation error on the unobservable subspace during the time interval T_i .

Choosing for the unobservable subspace (i.e. $span\{\bar{P}_i\}$) an estimator firstly of the form

$$\bar{P}_i \dot{\hat{Z}} = \bar{P}_i A_i (\bar{P}_i \hat{Z} + P_i \hat{Z}(t_{i,0})) + \bar{P}_i B_i u \quad (5)$$

and this for $t \in [t_{i,c}, t_{i,0}]$. And secondly for $t \in [t_{i,1}, t_{i,c}]$ the estimator becomes

$$\bar{P}_i \dot{\hat{Z}} = \bar{P}_i A_i (\bar{P}_i \hat{Z} + P_i Z) + \bar{P}_i B_i u \quad (6)$$

it is possible to use (6) after $t_{i,c}$ because the finite time as converged and consequently $P_i Z$ is perfectly known.

From equations (5) and (6) and conditions (3) and (4) the variation of V during the time interval I_i is

$$\begin{aligned} \Delta V &= V(e(t_{i,1})) - V(e(t_{i,0})) \\ &= \int_{t_{i,0}}^{t_{i,1}} \frac{\partial V(\cdot)}{\partial e} \big|_{e_{\bar{P}_i}} \bar{P}_i A_i e_{\bar{P}_i} dt \\ &+ \int_{t_{i,0}}^{t_{i,0}+k_i(t_{i,1}-t_{i,0})} \frac{\partial V(\cdot)}{\partial e} \big|_{e_{\bar{P}_i}} \bar{P}_i A_i P_i (Z - \hat{Z}(t_{i,0})) dt \\ &- V(e_{\bar{P}_i}(t_{i,0})) \end{aligned}$$

By integration continuity it is always possible $\forall l \in [1, +\infty]$ to find k_i such that

$$\begin{aligned} \int_{t_{i,0}}^{t_{i,0}+k_i(t_{i,1}-t_{i,0})} \frac{\partial V(\cdot)}{\partial e} \big|_{e_{\bar{P}_i}} \bar{P}_i A_i P_i (Z - \hat{Z}(t_{i,0})) dt \\ - V(e_{\bar{P}_i}(t_{i,0})) \leq \frac{V(e_{\bar{P}_i}(t_{i,0}))}{l} \end{aligned}$$

It is important to note that if $V(e_{\bar{P}_i}(t_{i,0})) = 0$, then $k_i = 0$ and this corresponds to the case where the finite time observer is initialized with the exact system

observable state value.

This choice of k_i implies that, for all time interval T_i , the variation of V verifies

$$\Delta V \leq -\frac{V(e_{\bar{P}_i}(t_{i,0}))}{l} - \int_{t_{i,0}}^{t_{i,1}} \frac{\partial V(\cdot)}{\partial e} \Big|_{e_{\bar{P}_i}} \bar{P}_i A_i e_{\bar{P}_i} dt$$

and from condition (4) and the linearity of (5) there exist the same $\lambda > 0$ for all i such that

$$\Delta V \leq -\frac{V(e_{\bar{P}_i}(t_{i,0}))}{l} - (e^{\lambda(t_{i,1}-t_{i,0})} - 1)V(e_{\bar{P}_i}(t_{i,1}))$$

With $V(e(t_{i,1})) = V(e_{\bar{P}_i}(t_{i,1}))$ and $V(e_{\bar{P}_i}(t_{i,1})) = 0$ the condition (2) implies that for any part of the state there exist at least one time interval I_i where this state part is observable then considering time interval from $t_{0,0}$ to $t_{N,1}$ the variation V verifies

$$-V(e(t_{0,0})) \leq \lambda V \leq -\frac{V(e(t_{0,0}))}{l}$$

Consequently

$$0 \leq V(e(t_{N,1})) \leq V(t_{N,1}) \leq \frac{1-l}{l} V(e(t_{0,0}))$$

As l can be chosen arbitrarily close to 1 the system is $Z(T_N)$ observable.

The application of Proposition 2 to the multicellular converter yields the following result :

Consider the system (1) (see Fig.1) . Let us assume that we can measure the input current $i_e = \sum_{i=1}^3 s_i x_i$ The system of parallel multi-cell chopper is not $Z(T_N)$ -observable with $Z = [x_1, x_2, x_3]$ for any time trajectory. The problem is to exhibit some particular hybrid trajectory T_N and $\langle T_N \rangle$ such that the system (1) is $Z(T_N)$ -observable. It can be verified that $Z = [x_1, x_2, x_3]_T$ is not $Z(T_N)$ -observable with any hybrid time trajectory under discrete status (1,1,1), (1,1,0), (1,0,1) and (0,1,1). However, if a trajectory of the system satisfies that the status is (1,0,0) in period I_1 , (0,1,0) in period I_2 and (0,0,1) in period I_3 , then $Z = [x_1, x_2, x_3]$ is $Z(T_N)$ -observable. We define in I_1 $P_1 = [1 \ 0 \ 0]$, similarly in I_2 and I_3 respectively $P_2 = [0 \ 1 \ 0]$, $P_3 = [0 \ 1 \ 0]$.

$$\text{Rank} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix} = n_z = 3,$$

this problem satisfies the assumption in condition (2).

Define the candidate Lyapunov function as:

$$V(X) = \sum_{i=1}^p x_i^2(t)$$

It can be verified that these function satisfying assumption 3

$$V(Z) = V(P_i Z) + V(\bar{P}_i Z);$$

In order to show that $V(X)$ verified the assumption (4) its first time derivative can be described as follows :

$$\dot{V}(\bar{P}_i) = -\frac{1}{2} \sum_{k \neq i}^5 \left(\frac{R}{L} x_k^2 + \frac{1}{L} x_k v_C \right) \leq 0;$$

4 OBSERVER DESIGN

Observer design1:

Assuming that the input current i_e and voltage output v_C are measured, the super-twisting observer for the system (1) is designed as follows[3]:

$$\begin{cases} \dot{\hat{x}}_i = s_i \frac{-R}{L} \tilde{x} + (1 - s_i) \frac{-R}{L} \hat{x}_i - \frac{-1}{L} v_C \\ \quad + s_i \frac{E}{L} \lambda |e_i| \text{sign}(e_i) \\ \dot{\tilde{x}} = s_i \left(\frac{-R}{L} \hat{x} - \frac{-1}{L} v_C + s_i \frac{E}{L} + \alpha \text{sign}(e_i) \right) \\ \tilde{x}(t) = \hat{x}_i(t), \quad \text{for } t_i^+ \leq t < t_i^0 \end{cases} \quad (7)$$

Where t_i^+ is the instant of transition of the switch control q_i passing from the closed state to the open state. λ and α are positive constants [3]. Define the observation errors as:

$$\begin{cases} e_i = i_e - s_i \hat{x}_i = \sum_{i=1}^p s_i x_i - s_i \hat{x}_i \\ \tilde{e}_i = \sum_{i=1}^p s_i x_i - \tilde{x} \end{cases} \quad (8)$$

Remark 2:

According to the above assumptions, there is a hybrid time trajectory such that the current phase is observable. When a switch s_i is closed the value of x_i is observed, outside this interval the current is estimated by the knowledge of the dynamics of the model and these parameters.

Equations (1)-(7)-(8) yield the dynamics of the observation error as:

$$\begin{cases} \dot{e}_i = s_i \frac{E}{L} \lambda |e_i| \text{sign}(e_i) - \frac{R}{L} \tilde{e}_i \\ \dot{\tilde{e}}_i = -\frac{R}{L} e_i - \alpha \text{sign}(e_i) \end{cases} \quad (9)$$

The system (9) can be approximated by a system of order two, where the eigenvalues of the dynamic matrix of the system are negative real parts; the trajectories will spiral into the origin. To ensure convergence

of \dot{e}_i you must calculate its dynamic, which is represented in the following equation:

$$\ddot{e}_i = \phi(e_i) - \frac{\lambda}{2}|e_i|^{-\frac{1}{2}}\text{sign}(\dot{e}_i) \quad (10)$$

Such that $\phi(e_i)$ converges to zero when the error convergence is guaranteed[7]. From equation (11) one can observe the convergence of the dynamics of the error \dot{e}_i

Observer design 2:

In this section, phase currents and voltage output will be observed using only the measurement of input current i_e . The observer design for the system (1) is represented as follows:

$$\begin{cases} \dot{\hat{x}}_i = s_i \frac{-R}{L} i_e + (1 - s_i) \frac{-R}{L} \hat{x}_i - \frac{1}{L} \tilde{x} \\ \quad + s_i \frac{E}{L} + s_i \lambda |e_i| \text{sign}(e_i) \\ \dot{\tilde{x}} = \frac{\sum_{i=1}^p \hat{x}_i}{L} - \frac{\tilde{x}}{RC} + \alpha \text{sign}(e_i) \quad i = 1, \dots, p \end{cases} \quad (11)$$

Remark 3: The estimated variable \hat{x}_i takes the value of x_i when the switch s_i is closed. In this interval the observer estimates the output voltage and the phase currents which the switches are open.

$$\begin{cases} e_i = s_i x_i - s_i \hat{x}_i \\ \tilde{e}_i = \frac{1}{C} \sum_{i=1}^p s_i x_i - \tilde{x} \end{cases} \quad (12)$$

Equations (1)-(11)-(12) yield the dynamics of the observation error as:

$$\begin{cases} \dot{e}_i = s_i \lambda |e_i| \text{sign}(e_i) - (1 - s_i) \frac{R}{L} e_i - \frac{1}{L} \tilde{e}_i \\ \dot{\tilde{e}} = -\frac{R}{L} e_i - \alpha \text{sign}(e_i) - \frac{1}{C} \sum_{i=1}^p e_i - \frac{1}{RC} \tilde{e} \end{cases} \quad (13)$$

According to Remark 2, the objective, i.e. the estimation of the current phases and voltage output, is achieved when the finite time stabilization of the system (14) is obtained.

5 SIMULATION RESULTS

The simulation is done to verify the theoretical results. The multiphase power converter has the aforementioned parameters: $E = 12V$, $L = 100\mu H$, $C = 100\mu F$, $R_L = 1m\Omega$ and $R_S = 0.035\Omega$.

First set simulation : phase currents are unbalanced.

The observer has been tested when the average values of current phases are unequal. Let now an

estimation of current phases be obtained as the noisy measurement of the input current and output voltage. Fig.2 and Fig.3 show the convergence of the first observer and error of observation. This observer estimates the phase currents from the knowledge of the control and the two measures of input current and output voltage. The figures also have a zoomed area to show convergence of the observer.

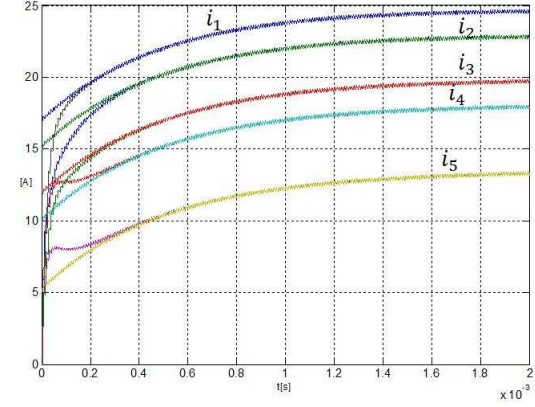


Fig.2 Phase currents (i_1, i_2, i_3, i_4, i_5) and their estimates ($\hat{i}_1, \hat{i}_2, \hat{i}_3, \hat{i}_4, \hat{i}_5$).

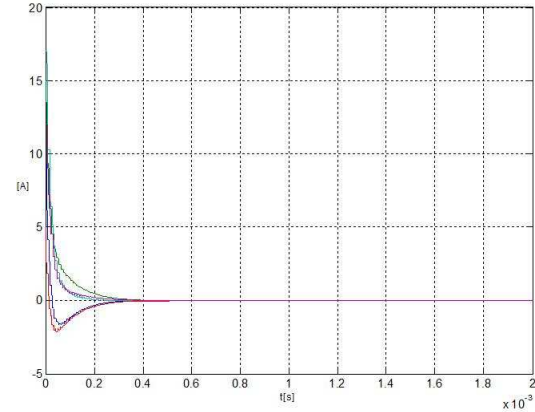


Fig.3 errors of observation e_1, e_2, e_3, e_4 and e_5 .

Second set simulation : observer using only the measurement of input current. The purpose of this part is the observation of phase currents and output voltage without the knowledge of the dynamic of load. The performance of the observer system is shown through Fig.4 and Fig.5.

For the simulations, the observer is set to operate in two load zones, incorporating disturbances of measurements and variations of current phases. The evolution of the current phases and their estimates is depicted in Fig.4. All observers converge exactly in finite-time despite of the perturbation measurements. Note that the high-order sliding mode observer improves the convergence velocity of the observation error. Once we have obtained the current phases and voltage output, we can now compute the parameters of the load.

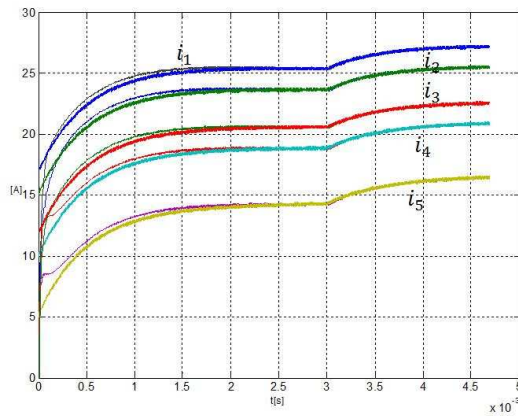


Fig.4 Load variation, phase currents and their estimations

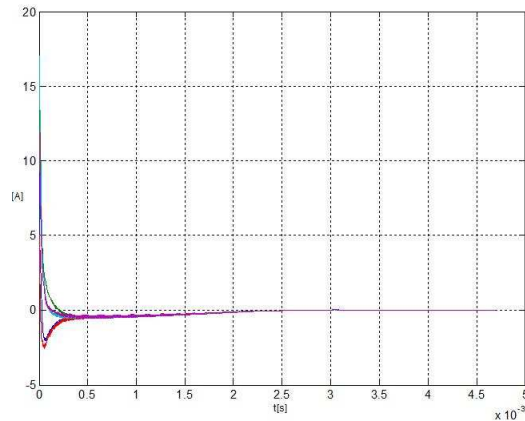


Fig.5 Observation errors in phase currents, variation of load at $t = 0.003s$.

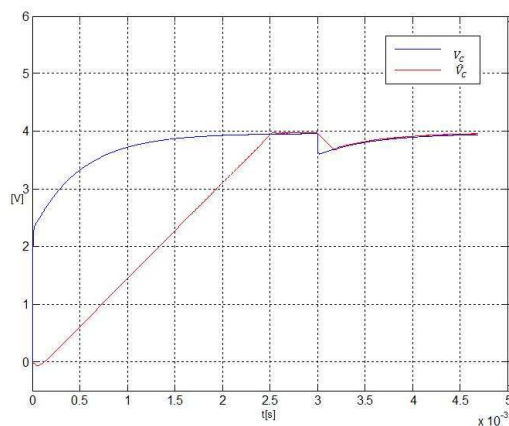


Fig.6 Output voltage v_C and its estimate \hat{v}_C .

6 CONCLUSION

In this paper, a new DC/DC multi-cell converter has been studied. The problem of the phase current and output voltage estimations is solved. In such situations, the $Z(T_N)$ observability for switched systems to be useful. The concept of $Z(T_N)$ observability is extended to hybrid dynamic systems, an algebraic characterization of the strong observability is intro-

duced for a 4-phases parallel multi-cell converter and an algorithm that yields a super-twisting observer based on sliding mode theory is applied. The robustness of the estimation method has been guaranteed using the high order sliding mode observer. Finally, the numerical simulations approve the obtained theoretical results. Further research is necessary to realize the control of output current, phase currents and output voltage without load variation and disturbance.

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